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# Scaling of Divertor Heat Flux Profile Widths in DIII-D

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## I. Introduction

The width of the divertor heat flux profile  $w_{q,div}$  is of great interest in future large tokamaks as well as many present devices. Previous studies examining the parametric dependence of  $w_{q,div}$  have arrived at diverse scalings [1] in JET [2], ASDEX-Upgrade [3], JT60-U [4,5], DIII-D [6,7], and NSTX [8] with results somewhat at variance with each other. We attempt here to perform a new series of experiments in DIII-D under controlled conditions to obtain scaling of the divertor heat flux peak value, profile width, and divertor plate power as a function of plasma input parameters, with the maximum number of divertor and scrape-off-layer (SOL) diagnostics brought to bear.

We performed measurements in lower single-null edge localized mode (ELM) H-mode diverted configurations that were not strongly pumped due to the strike-point positions. We varied the plasma current  $I_p$  at constant toroidal field ( $B_T$ ) and line-averaged density  $\bar{n}_e$  at constant  $I_p$  and  $B_T$ . The neutral beam injected power  $P_{inj}$  was changed at constant  $I_p$  and  $B_T$ ,  $B_T$  at constant  $I_p$ , and  $B_T/I_p$  at constant  $q_{95}$ . The divertor heat flux was calculated from infrared camera measurements using a new high-resolution fast-framing IR camera.

The IR camera recorded divertor plate surface thermal emission at many-kilohertz frame rates through the whole discharge, so that time-averaged data as well as rapid changes due to ELMs were obtained. The heat flux at each position in the radial profile was calculated at each of the times steps using the THEODOR 2D heat flux analysis code. We show scaling of the divertor peak heat flux and profile width as a function of the parameters varied, and compare with published results from other devices.

## II. Peak Divertor Heat Flux

For each discharge, one or more time intervals of interest were selected where plasma conditions varied little during the interval. The average of each quantity was compiled for each interval.

Figure 1 shows the peak heat flux at the inner (ISP) and outer strike points (OSP) plotted against the input power (neutral beam heating plus Ohmic heating power), where  $I_p = 1.3$  MA,  $B_T = -1.9$  T were held constant. Density was between  $5.2$  and  $6.5 \times 10^{19} \text{ m}^{-3}$ , except at the highest power, where  $\bar{n}_e = 2.3 \times 10^{19} \text{ m}^{-3}$ . Linear fits are shown. A linear dependence of peak heat flux on input power can reasonably be concluded, with the caveat that not all points were taken at the same density. Without the highest power point, we still see a linear dependence.

Figure 2 again shows peak heat flux at the ISP and OSP, this time plotted against line-averaged density, where  $P_{inj} = 4.6\text{--}4.7$  MW except for the densities  $\bar{n}_e = 5.2 \times 10^{19} \text{ m}^{-3}$ , where  $P_{inj} = 7$  MW, and  $\bar{n}_e = 6.8 \times 10^{19} \text{ m}^{-3}$  where  $P_{inj} = 3.8$  MW. Toroidal field was held constant at  $B_T = -1.9$  T, and plasma current were held at  $I_p = 1.3$  MA. Linear fits to the data are shown. If the two density values where  $P_{inj}$  varied are eliminated, the dependence of peak heat flux on density still is linear.

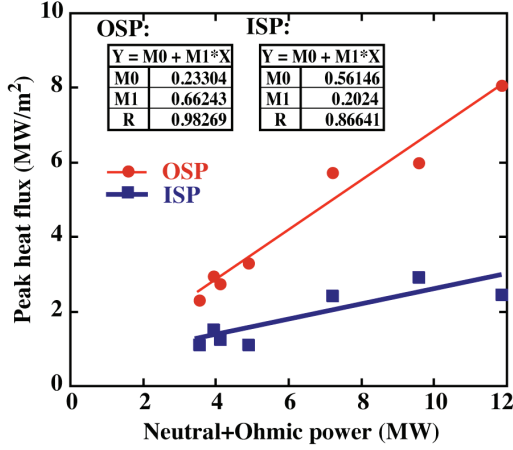


Fig. 1. Peak heat flux at the ISP and OSP plotted against the input power. Linear fits to the data are plotted, with fitting parameters shown in the boxes.

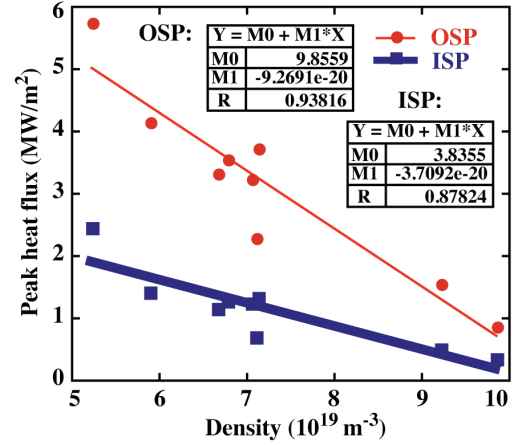


Fig. 2. Peak heat flux at the ISP and OSP plotted against line-averaged density.

Figure 3 depicts the peak heat fluxes, now plotted against plasma current, showing a linear dependence. Toroidal field was held at  $B_T = -1.9$  T, and  $P_{inj} = 4.65\text{--}4.8$  MW except for the point at  $I_p = 1.3$  MA where  $P_{inj} = 3.8$  MW. Density was not held constant, but allowed to vary at the natural H-mode density, because of practical difficulty measuring the heat flux at the OSP during the plasma pumping that would have been required to maintain constant density. Figure 4 shows the density variation during the IP scan. Because of the density variation in this set, this plot does not prove the variation with IP alone. In combination with the density scan at constant  $I_p$ , the dependence on  $I_p$  will be extracted from a multi-parameter fit to a larger data set in a later analysis.

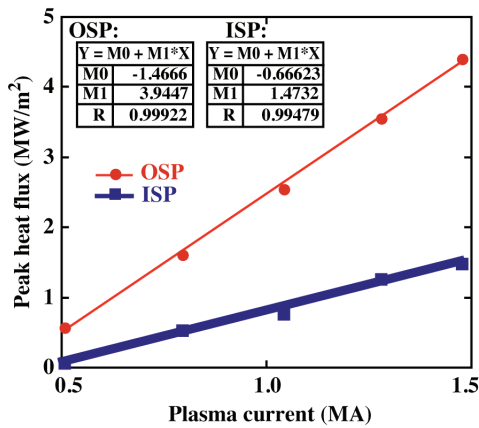


Fig. 3. Peak heat fluxes, now plotted against plasma current.

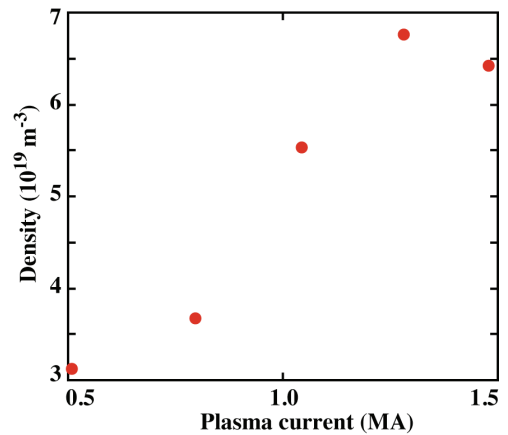


Fig. 4. Density variation during the IP scan.

Figure 5 shows peak heat fluxes plotted against  $B_T$  at nearly constant safety factor  $q_{95} = 3.6$ – $3.7$ , with linear fits. Density ranged from  $\bar{n}_e = 3.2 \times 10^{19} \text{ m}^{-3}$  at the lowest field to  $\bar{n}_e = 5.8 \times 10^{19} \text{ m}^{-3}$  at the highest field. There are not enough data points to conclusively show a linear dependence, but that would be consistent with the data. Since we know from Fig. 2 that the peak heat flux decreases with increasing density, this indicates that if density were held constant, the heat flux would increase faster than linearly with increasing toroidal field magnitude at constant  $q_{95}$ .

### III. Heat Flux Profile Width

Profile widths discussed here are full width at half maximum (FWHM) values for the ISP and OSP respectively. Widths are obtained at each time point and averaged over the time intervals of interest. Here  $w_{q,\text{div}}$  shows no dependence on input power (not shown).

Figure 6 shows the outer and inner  $w_{q,\text{div}}$  plotted against density, for the same density scan as above. There is no effect at low density, but there is a threshold density where the profile becomes wider.

In Fig. 7 is seen  $w_{q,\text{div}}$  plotted against  $I_p$ , for the current scan already described. We see that widths become larger at low current. The fitted curve for the ISP is linear, but for the OSP, a better fit goes inversely as nearly the first power of the plasma current. No ISP heat flux peak was seen at the lowest  $I_p$ . We expect the current dependence of the inner width would be of a similar functional form to that of the OSP if more data were available. Note in Fig. 3 that the peak heat flux for this case at the ISP is very small.

The plot in Fig. 8 shows  $w_{q,\text{div}}$  versus toroidal field at constant  $q_{95}$  for the same discharges as described for the peak heat flux scaling. The widths decrease linearly with the magnitude of the toroidal field.

### IV. Comparisons With Other Empirical Scalings

Loarte summarized several empirical scalings in Ref. 1, pointing out the areas of disagreement. Here we compare the functional dependences seen above with those scalings.

The linear dependence on power seen above is in agreement with the JET, ASDEX-Upgrade (DIVIII), and previous DIII-D scaling, but not the ASDEX-U (DIVI) scaling. We note that several of those studies use divertor or target power rather than input power. We find the same linear correlation of peak heat flux with target power as with input power.

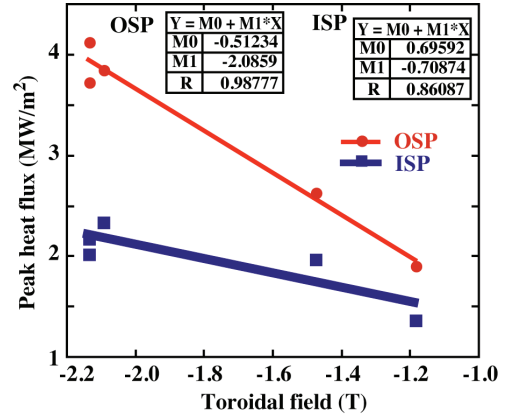


Fig. 5. Peak heat fluxes plotted against  $B_T$  at nearly constant safety factor.

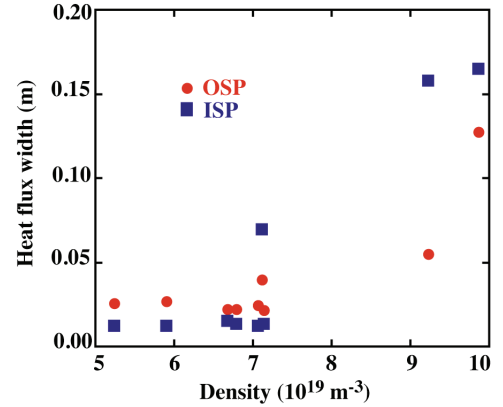


Fig. 6. OSP and ISP heat flux profile widths plotted against density.

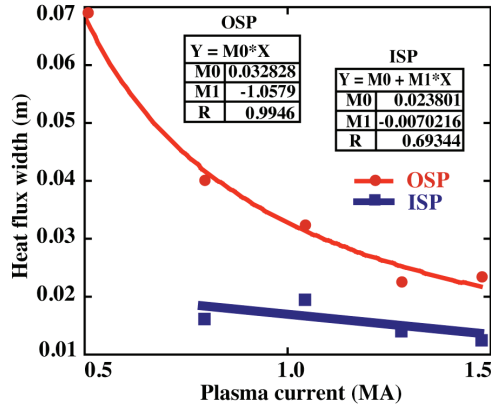


Fig. 7. Profile widths plotted against plasma current.

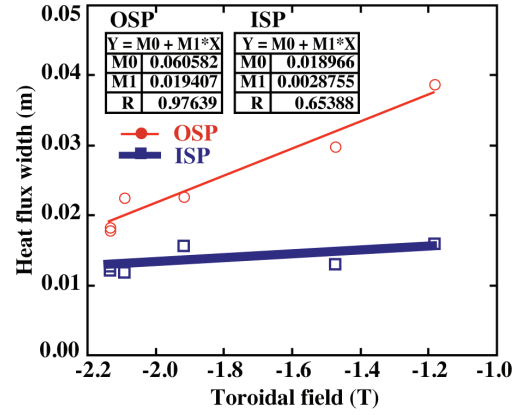


Fig. 8. Profile widths versus toroidal field at constant  $q_{95}$ .

We have not observed a clear dependence of peak heat flux on toroidal field on the present data, unlike the previous DIII-D study which found a variation of  $1/B_T^{0.5}$ . A later multi-parameter fit may show a dependence. The linear increase in peak heat flux with  $I_p$  peak agrees with the previous DIII-D result.

The  $w_{q,div}$  we use here is different than the  $\lambda_q$  of the referenced studies, which defined an effective width by dividing the strike point power by the peak heat flux. We find in agreement with NSTX, JET IR and ASDEX-Upgrade (DIVII), essentially no (or very weak) dependence of the width on power. We find in agreement with NSTX that the width decreases with increasing plasma current, approximately as  $1/I_p$ .

## V. Conclusion

In the present study we find that peak heat flux varies linearly with input power, inversely as density, linearly with plasma current with a caveat that density was not fixed, and linearly with the magnitude of the toroidal field with  $q_{95}$  held constant.

We find FWHM  $w_{q,div}$  depends not at all on power, and not on density at low density. There is a density threshold for profile broadening. We see  $w_{q,div}$  varies inversely with the  $I_p$  and decreases linearly with increasing  $B_T$  at constant  $q_{95}$ . This is the opposite direction of the dependence on  $I_p$ , so this is not simply due to the increase in  $I_p$ .

We expect to examine this data set further with other fitting techniques as well as making a study of the ELM heat flux profiles from the parameter scans above.

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